



New and Improved Superstring Phenomenology

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Abstract

Recent developments in string theory have important implications for cosmology. Topics discussed here are inflation, the cosmological constant, smoothing of cosmological singularities, and dark matter from parallel universes. Talk presented at the International Workshop on Particle Physics and the Early Universe (COSMO-98), 15-20 Nov, Asilomar, Monterey, CA.

Lost in (Moduli) Space

The duality revolution which occurred during the past five years has enormously advanced our knowledge and perspective regarding the theory formerly known as superstrings. There is now overwhelming evidence[1] to the effect that there is a unique string theory (often called M theory), which contains, in addition to strings, a variety of membranes and even particle-like objects. In a kind of Planckian democracy, none of these degrees of freedom can truly be regarded as more fundamental than the others. In fact in one limit of this theory (somewhat confusingly called the M theory limit), the string degrees of freedom are completely absent. This recent explosion of our understanding of nonperturbative string physics nicely complements the impressive edifice of perturbative string knowledge built up during the previous decade. All of which leads to the obvious question:

- If we know so much about string theory, why can't we predict anything?

The main reason for this embarrassing irony is that string theory does not have a unique (consistent, stable,) ground state. This was known to be true at the perturbative level for many years, but only recently have we realized that this disturbing property appears to persist even when we bring to bear our full arsenal of nonperturbative string dynamics. At low energies string theory is described (mostly, at least,) by an effective field theory; without a definite choice for the string vacuum we cannot even specify the degrees of freedom of this low energy theory, let alone the form or parameters of the effective lagrangian.

The problem is that we are lost in moduli space. The effective field theory limit of string theory contains a number of scalar fields, called moduli, with flat potentials. This is not surprising since most known string vacua preserve some spacetime supersymmetry, and moduli are a generic feature of supersymmetric field theories. We can parametrize a moduli space by the vacuum expectation values (vevs) of these scalar fields. As we move around in this moduli space, the effective field theory, defined by shifting by these vevs, can vary enormously. Not only are there variations in couplings, but at special points in moduli space the number and type of light degrees of freedom changes.

We have only just begun to feel our way around the intricate tapestry which represents the full moduli space of consistent string vacua. We have probed around the edges, which represent the various possible perturbative limits of string theory, as well as the 11-dimensional (non-stringy) M theory limit. The interior remains largely *terra incognita*, although string duality relations help us trace the threads connecting these different limits. We know neither the dimensionality nor the topology of the full string moduli space. Nor do we know the connectivity of this space. The tapestry may be very frayed, with many ragged patches connected to the main body by only a few threads; there may even be “string islands”, points or patches of moduli space completely disconnected from the main body.

One (at least) of these points ought to correspond to the Standard Model particle physics and FRW cosmology that we observe at low energies and long distance scales. But where?

Moduli and Cosmology

It is not surprising that the existence of moduli fields has implications for cosmology. Indeed this is true even for approximate moduli, i.e., scalars whose flat potentials are lifted by nonperturbative effects. Since the number and type of moduli vary as we move around in moduli space, most of what we can say about string cosmology is very dependent on where we think the string ground state is.

Certain moduli, however, have slightly more robust characteristics. Perturbative limits of string theory contain a dilaton, a weakly coupled scalar whose vev determines the string coupling, and thereby the basic relationships between the Planck scale, compactification scales, and gauge couplings. These same perturbative limits also contain a pseudoscalar axion, and indeed axions seem to be generic features of large classes of string vacua. Compactified dimensions in string theory can assume a wide variety of geometries; nevertheless certain features of the modulus describing the “overall” scale of compactification are somewhat generic.

Another interesting class of moduli for cosmology are what I will call “invisible” moduli. The vevs of these scalars describe either dimensionless couplings or new mass and length scales associated with hidden sectors—exotic matter and gauge fields which couple only gravitationally to ordinary matter.

The good news for cosmologists is that string moduli provide natural candidates for the scalar fields that may perform some cosmologically important tasks. These include the inflaton and perhaps quintessence. The bad news for cosmologists is that generic regions of string moduli space won’t look good cosmologically. Indeed generically moduli are more likely to be a cosmological headache than a panacea. The devil, furthermore, is in the details, and generically these details are difficult to tackle.

The dilaton, for example, has properties which make it an attractive candidate for the inflaton[2, 3, 4]. The dilaton acquires a nonvanishing potential only from nonperturbative effects; the relative gradient in this potential is naturally of order the inverse Planck mass, as desired for slow roll inflation. On the other hand, there are a number of problems with dilaton inflation[5, 6, 7]. Specific scenarios require additional assumptions about the nonperturbative contributions to the potential; these assumptions are hard to pin down with our current level of knowledge. In many scenarios there is the

additional problem that the dilaton kinetic energy dominates the potential energy. Furthermore, near any of the perturbative limits of string theory, the dilaton is generically unstable; it's vev wants to run off to infinity, producing an infinitely weakly coupled theory. One can postulate nonperturbative fixes for this runaway behavior, but such scenarios are neither rigorous nor robust.

String Islands and the Cosmological Constant

The cosmological constant problem is the most notorious and vexing problem of quantum gravity[8]. Any attempt to unify quantum mechanics with gravity leads (at least naively) to the conclusion that quantum fluctuations in the vacuum (i.e. zero-point energies) must couple to gravity. Since these zero-point energy sums are typically divergent, their natural scale in a quantum field theory is some ultraviolet cutoff U . One thus expects to generate a cosmological constant of order

$$\Lambda \sim U^4 \quad , \quad (1)$$

and that the entropy associated with a system of linear size L scales like

$$S \sim L^3 U^3 \quad . \quad (2)$$

Note that Λ is positive if bosonic modes dominate the sum, and negative if fermionic modes dominate. Supersymmetric vacua have zero cosmological constant, due to bose-fermi cancellations.

The cosmological constant problem arises because any reasonable choice for the ultraviolet cutoff scale U leads to a Λ which exceeds the observational upper bound by a ridiculously large multiple, roughly 10^{-100} (here I am invoking “roughly” as per standard usage in cosmology, meaning order of magnitude in the exponent). This is because particle physics scales such as the Planck mass (10^{19} GeV), the Standard Model Higgs vev (10^2 GeV), and the apparent supersymmetry-breaking scale ($10^2 - 10^3$ GeV), greatly exceed the energy scale characterizing the current matter density of the universe (10^{-3} eV). This is a disturbing problem, made worse by our desire to allow a rather large effective Λ during an earlier inflationary epoch. It should also be noted that recent ideas about quintessence in no way address the main cosmological constant problem; rather quintessence models evolve one very small effective Λ value to another very small effective Λ value.

String theory, which is (if nothing else) a consistent theory of quantum gravity, ought to give us some profound insight to this problem. Unfortunately even with recent advances of the duality revolution, the cosmological constant problem remains a complete mystery even in string theory.

A possible ray of hope is provided by a suggestion of Witten[9], which ties in nicely[10] to some recent work on the idea of “string islands”. Witten observed that in 2+1 spacetime dimensions you can have supersymmetry of the vacuum (and thus $\Lambda=0$) without supersymmetry of the spectrum (i.e. no bose-fermi degeneracy for particles). Furthermore, string theory in 2+1 dimensions actually becomes string theory in 3+1 dimensions in the limit where the string coupling (determined by the dilaton vev) goes to infinity. This peculiar phenomenon is similar to that which leads to the 11-dimensional M theory limit. The strongly-coupled 2+1 dimensional string theory has light solitons, which actually behave exactly like a set of light Kaluza-Klein modes. These solitonic degrees of freedom thus represent the degrees of freedom of a third spatial dimension compactified on a circle. In the strong coupling limit the radius of this circle becomes infinite, and a 3+1 dimensional theory results.

This suggests a method for finding non-supersymmetric string vacua with zero cosmological constant, by starting with 2+1 dimensional string vacua which contain a dilaton. Note that it is important for this trick that the 2+1 string vacua do not contain any geometrical moduli associated with compactifications from higher dimensions. Such moduli would invalidate the original argument, leading presumably to a nonzero Λ whose scale is set by the square of the bose-fermi mass splittings divided by the compactification scale; this is too large unless we manage to keep all the mass splittings below about 100 GeV.

Thus the pure version of this trick requires string islands (peninsula?): string vacua which contain the dilaton and its axion partner, but do not contain any geometrical moduli. Surprisingly, such string islands are known to exist even in the weakly-coupled limit of the heterotic string[11]. There is, for example, a 3+1 dimensional string vacuum whose low energy limit is pure 3+1 dimensional $N = 4$ supergravity. Many more examples have been constructed recently[12].

I should emphasize that even if one could exhibit string islands corresponding to non-supersymmetric vacua with zero cosmological constant, it is another matter entirely to show that any such vacuum is consistent with

the Standard Model. An important conclusion for cosmologists, however, is that current thinking about making string vacua which are more “realistic” seems to favor reduced sets of moduli. A broader conclusion is that in the long run cosmological considerations are likely to play an important role in resolving mysteries about the vacuum state of string theory.

Delightful D branes

As mentioned above, string theory abounds with membranes of various types and dimensionalities. Of particular interest are D branes, objects which, considered as backgrounds for string propagation, preserve part of the underlying spacetime supersymmetry. D branes have a number of special properties, and occur with various dimensionalities (thus we have D instantons, D particles, D strings, and D membranes with up to 9 spatial dimensions). From the string point of view a D brane is a soliton whose mass (or tension, or mass per unit volume) is proportional to the inverse of the string coupling g_s . This means, among other things, that D branes become light in those regions of string moduli space where the string coupling is large.

This simple fact has led to a new interpretation for singularities of various fixed spacetime backgrounds in which strings propagate. These singularities are associated with compactifying some of the original 9 or 10 spatial dimensions onto orbifolds, conifolds, or other singular geometries. A D brane can wrap around a D-dimensional closed cycle of this compact space; when this cycle is shrunk to a point a singularity appears, associated with the vanishing mass of the wrapped D brane. This observation provides a generic and physically intuitive mechanism for “smoothing” spacetime singularities.

The obvious question, of course, is whether this D brane smoothing also applies to cosmological singularities. Recent work suggests that the answer is yes[13, 14], although perhaps not in all cases[15]. This is an exciting avenue for future research.

Dark Matter in Parallel Universes

The mass scale at which string physics becomes stringy is known as the string scale, m_s . For the weakly coupled heterotic string, the string scale can be

shown to be about 10^{18} GeV, only about an order of magnitude smaller than the Planck mass, m_p . However in other regions of string moduli space the string scale can be much smaller[16]. Since we don't know where we are in moduli space, we also don't know the value of m_s . The most we can say at present is that m_s is greater than about 1 TeV, due to nonobservation of stringy effects in the Tevatron collider experiments[17].

It is tempting to imagine[17] that perhaps the string scale is not too far above the current lower bound, in the multi-TeV region which will eventually be accessible to colliders. If this bold hypothesis is correct, we are immediately faced with the problem of explaining the small ratio m_s/m_p . In string theory this small ratio is presumably related to certain moduli having very large or very small vevs, as measured in units of m_s . If these moduli are “invisible” moduli of the type discussed earlier, then their existence may have no other direct consequences for observable low energy physics.

On the other hand, this small ratio could be a consequence of large compactified dimensions[18, 19], through a scaling relation like

$$m_p^2 \sim m_s^{n+2} R^n \quad , \quad (3)$$

where R is the size of the large compact dimensions, and n is the number of such dimensions. For m_s of order a TeV and $n \geq 2$, R in the above relation can be as large as 1 mm!

Actually, this form of the large extra dimensions scenario is completely ruled out by particle physics constraints, unless we make an additional bold hypothesis: that the entire Standard Model gauge theory is confined to live on a membrane orthogonal to the large extra dimensions. Since D branes are known to have supersymmetric gauge theories confined to their world-volumes, this hypothesis fits rather nicely with our current picture of string theory. If correct, the graviton has many massive Kaluza-Klein copies, but the Standard Model particles know of the existence of large extra dimensions only through coupling to gravity. There are, not surprisingly, many interesting cosmological implications of this scenario[19, 20, 21].

One intriguing observation is that, if the Standard Model gauge theory is confined to some configuration of branes, then there may be other gauge theories confined to other brane configurations, separated from us in one or more of the large extra dimensions. Such hidden sectors are very much like parallel universes, except that they are gravitationally coupled to the visible

universe. If these other “brane-worlds” contain stable matter, planets, stars, galaxies, etc., these will all appear to us as dark matter. Since the laws of (non-gravitational) physics could be quite different in these parallel worlds, qualitatively new forms of macroscopic matter may also be produced. It would be interesting to determine the current observational bounds on (i) dark “planets” in the vicinity of our solar system, (ii) dark “stars” within our galaxy and the galactic halo, and (iii) the density and distribution of dark “galaxies”.

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